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Forest carbon sequestration supply function for African countries: An econometric modelling approach

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ABSTRACT

Carbon sequestration cost function for developing nations particularly Africa plays a vital role in global climate change policy. Based on this, the study estimates carbon sequestration supply function for African countries. The study shows that majority of the selected countries have their cost of carbon sequestration estimated at \$14 per ton per ha. Botswana and Congo DRC represent African countries with high cost of carbon sequestration with \$16.75 and \$16.77 respectively. Nigeria however, has her average cost of carbon sequestration as low as \$6.82. The regression result shows that carbon sequestration supply ($p < 0.01$), deforestation ($p < 0.01$) and forest area ($p < 0.01$) are the factors influencing cost of carbon sequestration among the sub-Saharan African countries. The overall marginal cost which is the cost per unit land area required to drive land use change towards carbon sequestration was estimated at \$13.30 per ton/ha in Africa. Nigeria, Mali and Chad however, show a relatively low marginal cost of \$7.0, \$8.0 and \$9.0 respectively. The study however suggests that positive land use characteristics should be encourage among countries in Africa, particularly in Nigeria with the least marginal cost of carbon sequestration. This will help in reducing cost of carbon sequestration and thereby lowering the global effect of climate change.

1. Introduction

Greenhouse gases (especially carbon) have been found to be the major cause of global warming and developed nations of the world have been found to be the major emitters of carbon (Bala, 2014). Natural forests store a large quantity of carbon, thereby acting as “sinks” to heat trapping “greenhouse gas” providing means of addressing global warming (Condit, 2008). Increasing concerns about the threat of global climate change has brought with it greater attention to the possibility of encouraging the growth of forests as a means of removing carbon dioxide (CO_2) from the atmosphere (Lubowski et al., 2006). Studies have suggested that forestry-based carbon sequestration is a relatively inexpensive means of regulating carbon emission among developed nations against other means of carbon abatement (Dudek and LeBlanc, 1990; Sedjo and Solomon, 1989).

The need to reduce carbon emission has enhanced investment in forest based carbon sequestration particularly in developing countries by the major carbon emitting countries like USA, China, Japan etc. following different carbon trade mechanism established by the Kyotol protocol (IPCC, 2007; Nobi, 2013).

Globally, Africa particularly the sub Saharan African (SSA) are naturally endowed with forest area with which a large number of global carbon could be stored (Dieng et al., 2009). Unfortunately, the rate of deforestation and other unhealthy land use practices in this region of the world has contributed to global carbon emission rather helping the situation (FAO, 1999). It should be noted however, that most SSA countries are agrarian in nature with increasing population. This peculiarity contributes to increasing land use conversion (i.e. more deforestation) with less concern for the environment.

Substantial effort has been contributed towards ensuring carbon sequestration potential of SSA countries (Rohit et al., 2006). These include project implementations that will ensure reducing deforestation, afforestation, reforestation etc. with the aim to reduce cost of carbon sequestration globally particularly for high carbon emitting countries – as part of the flexibility of kyotol protocol.

Achieving land use change in SSA may results in conversion of land from the existing use (agriculture) to forest through afforestation and or reforestation. The cost of achieving these land use change among SSA countries plays an important role in determining whether developed nations would meet their emission target through flexible mechanism.

Hence, if the developed nations are to receive carbon sequestration services from African countries, the cost of carbon sequestration would be the major determinant. This however, is influenced by land use characteristic like deforestation halt, afforestation, reforestation among

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others (Nobi, 2013).

Therefore, the study seeks to estimate carbon sequestration supply function in SSA by estimating the marginal cost required per unit land area in driving land use towards carbon sequestration among the selected SSA countries, and discuss the implications of the estimated cost in relative to carbon market participation and climate change policy.

2. Literature review

2.1. Methodological review

There have been three main approaches used in estimating cost of carbon sequestration: “bottom-up” engineering models, sectoral optimization studies, and econometric models. According to Dempsey et al. (2009) these different cost estimation methods do not provide consistent cost estimates of forest-based carbon sequestration. It is important to understand the effects of the calculation method on the final results before accepting the cost estimates provided by any study.

Although, each of the three cost estimation approaches are concerned with measuring opportunity costs – what the landowner gives up when he or she converts land from a non-forest use such as agriculture to forest. Bottom-up and sectoral optimization methods measure these costs as the lost profits from the original use (e.g., agriculture) plus costs of establishing trees. Econometric approach, on the other hand, are based on how landowners actually respond to incentives they face in the market place.

As examined by Richards (2004), bottom-up engineering models generally use regional average land prices or land rents to estimate the opportunity cost of converting land from the existing use to another (Dudek and LeBlanc (1990); Moulton and Richards (1990); New York State (1991); Richards et al. (1993); Richards, 1997; Sedjo and Solomon (1989); Van Kooten et al., 1992). These values measure the foregone profits from agricultural production. Usually, the calculated opportunity cost is combined with the conversion costs for moving land from agricultural to forest use, and this becomes the total opportunity cost of the land. Total costs are expressed on an annual basis and divided by an annualized measure of carbon sequestration to obtain the cost per unit of carbon sequestered (or the average cost of carbon sequestration) based on this, the engineering method has advantages of using observable information and transparency of the calculations. However, a downside of the engineering method, and a likely source of the differences in cost estimates provided by the engineering method compared to the econometric approach, is the inability to account for unobservable factors affecting landowner decisions.

The sectoral optimization models typically combine market models of agriculture and forestry and account for the interaction between the two sectors (Adams et al., 1993; Alig et al., 1997; Sohngen and Mendelsohn, 2003). Like engineering models, optimization models are not able to account for unobservable cost and benefits to landowners, however, they do account for the increase in scarcity and, therefore, returns to agricultural land as more land is converted to forestry.

However, the econometric carbon sequestration cost studies analyse data from actual land-use changes with the goal of identifying the relationship between land-use choices and relative returns in the forestry, agricultural, and other land sectors (Stavins and Richards, 2005). Based on this, the econometric calculation method removes a level of uncertainty that is found in many engineering models, leading in principle to more realistic predictions of how landowners will behave. Because they are based on actual historical data, these models can implicitly capture such factors as landowner uncertainty in the face of irreversible investments, non-monetary returns to landowners from forest and agricultural uses of land, liquidity constraints, and other private or market costs or benefits (Lubowski et al., 2006). In addition, the survey based study by Van Kooten et al. (2002) demonstrates why the unobservable incentives that are captured in the econometric method are so important.

Hence, the econometric approach produces higher cost estimates than both the engineering and optimization methods. The most likely reason is that the econometric approach can account for a number of factors that affect land-use decisions in practice, but which are difficult to measure explicitly and include in engineering and optimization models. Several studies have considered the use of econometric approach as a suitable approach to estimating cost of carbon sequestration (Kerr et al., 2001; Newell and Stavins, 2000; Plantinga et al., 1999, and Stavins, 1999).

2.2. Theoretical framework

Producers who desire to earn profits must be concerned about both the revenue (the demand side of the economic problem) and the costs of production. The relevant concept of cost in this aspect is “opportunity cost.” This is the value of the next best alternative use of a resource (i.e. land). It is the value sacrificed when a choice is made. The motive for land use diversification among land owners is that of profit maximization utility. The theoretical tools that explains this are utility functions and budget constraints i.e. every producer will wish to maximize profit subject to resource constraint i.e. available land area. For a landowner to shift from one form of land use to another, his aim will be to get higher profit subject to his limited resource.

According to Nobi (2013), let A_0 be the total land supply which the landowner can use in conventional agriculture or in carbon sequestration. It is assumed that every landowner is profit motivated. So, given the available land, they will decide how much land to use in conventional agriculture and for carbon sequestration while the total supply of land is fixed. Then, the objective function of a firm or land owner is to maximize the following profit function (Π) subject to total supply of available land (A_0) (Appendix A).

For a landowner to achieve profit maximization, the marginal net returns of land use in both sectors (agriculture and carbon sequestration) needs to be equal, this is achieved by taking the first derivative which is the necessary condition i.e. First Order Condition (FOC) derived from the Lagrangian which is the marginal return of land use (Appendix A).

That is any firm or landowner will allocate his/her land use in agriculture and in carbon sequestration project in such a way that the marginal net return/profit is equal to ?? in both sectors (Appendix A).

3. Methodology

3.1. Modelling carbon sequestration supply function

The cost of carbon sequestration in carbon reduction project mainly depends on the opportunity cost of land, costs of maintenance, transaction and plantation. Deveny et al. (2009) has made it known that except for the opportunity cost of land, the other costs involved in land use change conversion towards carbon sequestration are negligible, and it considered all other costs as transaction cost (like growing and protecting a forest, human labour cost and machinery) which is estimated only 13% of the project cost.

In addition, the cost function has some exogenous determinants like Clean Development Mechanism (CDM) projects and Per-Capita Gross Domestic Product [GDP]. The GDP was converted to international dollars using Purchasing Power Parity (PPP). Carbon sequestration potential could, in theory, be very significant in terms of the CDM. If there is a CDM project in a country it will affect the rate of carbon sequestration and thereby influencing the cost of carbon sequestration (Cédric et al., 2007). This is because the presence of a CDM projects in a developing country implies that more lands are used in favour of CDM project which will increase the cost of carbon sequestration. Per Capita GDP (in PPP) is the indicator of economic growth and development and hence an indicator of carbon dioxide emission (Kaya, 1990). Economic growth and emission are positively related. Higher economic growth

Table 1
Summary of the data sources and measurement.
Source: Compiled from Data Sourcing, 2016.

Variable	Measurement	Source (Year)	Variable Type
Total cost (TC)	(Million USD)	Deveny et al., (Forest Carbon Index 2009)	Dependent
Carbon sequestration supply (CSS)	(Million ton)	Niles et al. (2002)Deveny et al. (2009)	Independent
Afforestation/reforestation rate (RR)	(1000 ha)	Niles et al. (2002) & FAO Forest Data	Independent
Deforestation (D)	(1000 ha)	Niles et al. (2002)	Independent
Deforestation halts (DH)	(1000 ha)	Niles et al. (2002)	Independent
Sustainable agriculture practice (SAP)	(1000 ha)	Niles et al. (2002)	Independent
Forest area (FA)	(1000 ha)	World Bank	Independent
Clean development mechanism (dummy)	(1 = present,0 = otherwise)	CDM Pipeline, UNEP Riso Centre (2012)	Independent
Per capita GDP, PPP	Current International Dollar	World Bank Data	Independent

relates to higher emission and lower economic growth relates to the lower emission. But lower emission also indicates emission reduction as well. Most of the developing countries are agrarian and less industrialized. As a result, increasing higher Per Capita GDP means higher production, more emission and more use of land in other cultivation sectors rather than carbon sequestration. As per capita GDP increases the opportunity cost of land use will increase in carbon sequestration, which affects the cost function. Furthermore, if the per capita GDP increases in a country it means that more lands are used in favour of other sectors. In that case, land use in favour of carbon sequestration will be costlier based on the need for land use conversion (Nobi, 2013).

The carbon sequestration cost function also depends on land use changes like afforestation/reforestation, sustainable agricultural practice, deforestation halted and size of forest area. For instance, the more the afforestation/reforestation takes place, the more land is distributed in favour of carbon sequestration, and thereby increasing the opportunity cost of land. Rokityanskiy et al. (2007) stated that tropical countries are feasible for afforestation which is better than the mature forest in terms of carbon sequestration as plantation accumulates higher rate of carbon sequestration (Bloomfield and Pearson, 2000). If the reforestation rate increases it will increase the cost of sequestration. Sedjo et al. (2001) reported that an average of 33–44% carbon reduction could be met cost effectively through forest-based sequestration.

Conventional agriculture system is claimed to be an important source of carbon emission. Small holder farming (small farm size) and use of irrigation pumps in agricultural sector are mainly responsible for carbon dioxide emission which is very common in Sub-Saharan African countries. Using pumps for irrigation emits carbon and thus it contributes to climate change. But energy efficient small-scale pumps can reduce farmers running costs and keep carbon dioxide emission at low rate (Sugden, 2010). Thus, sustainable agricultural practice is an indicator of land use which can affect the carbon sequestration in the developing countries.

Reduction of deforestation and degraded forests is an important source of carbon emission reduction by increasing sequestration. Avoiding deforestation has some other indirect benefits like biodiversity, water and air quality and maintenance of local climate (Bloomfield and Pearson, 2000). In order to avoid deforestation, land owner needs to be compensated as they have the opportunity to produce other commodity in their land which also increase the cost of carbon sequestration. Thus, the implementation of these practices affects carbon sequestration through land use change and thus influencing the cost of carbon sequestration. If a change in any of these determinants increases the volume of carbon sequestration, it will also increase the cost. These variables work as instrument in the carbon sequestration which in turn affects the cost function.

Forest area is another important determinant of carbon sequestration. If the size of a forest increases it will increase carbon sequestration. Sedjo and Solomon (1989) emphasized the need for expanding forest areas to offset world's carbon sequestration (cited from Richards, 2004). As forest is considered as the sink of carbon sequestration thus it is expected that the area of forest is proportionately related to the carbon sequestration.

3.2. Data sources and transformation

The study sites cover a total of 19 SSA countries. Other countries were not included due to lack of necessary data like land use change characteristics and CDM. The data used in this study was obtained from secondary sources following the procedure adopted by Nobi (2013). The data for different variables were collected from different sources like Niles et al. (2002), FAO, UN Data, CDM Pipeline, World Bank and some published journals.

Total cost of carbon is simply calculated by multiplying the Average Unit Cost (AUC) of carbon by Sequestered Quantity of Carbon (S) i.e. TC = AUC*S. Average unit cost is presented in USD per ton carbon in Forest Carbon Index estimation by Deveny et al. (2009). The author calculated the cost for one ton of carbon sequestration in different developing countries from which the selected countries were drawn. Carbon Sequestration data was collected from Niles et al. (2002). The estimates of carbon sequestration from different land uses are then added to get the total sequestration (from reforestation, deforestation halted and sustainable agriculture practice) where they have estimated the carbon sequestration for each activity separately. The data accounted for a period of 2003–2012 in million tons of carbon. Reforestation/afforestation rate, Deforestation and deforestation halted (1000 ha per year), sustainable agricultural practice (million ha per) were jointly collected from Niles et al. (2002). Data on forest area was obtained from World Bank country data for each of the selected countries. In the data set, it was expressed as square kilometre but for the purpose of uniformity with other variables, it was converted to hectare. The CDM project data was extracted from CDM Pipelines under UNEP Riso Centre (March 2012). Finally, the Per Capita GDP, measured in PPP, was used as extracted from the World Bank data (2012). The GDP data was expressed in current international dollar. Summary of the data sources, measurement and year of the data is presented in Table 1. Table 2 presents the descriptive statistics of the raw data.

3.3. Data analysis and model specification

After the data gathering, mathematical and statistical diagnosis were conducted to check whether the data satisfy normality condition. Normality is the most important characteristics of the raw data. It was observed that the data follows normality (with higher p-values) after taking a natural log of each of the variable. The CDM was excluded since a natural log of zero (0) is undefined. Result of the normality test is presented in Table 3.

Carbon sequestration is a function of land use characteristics. In this study, land use characteristics are not included in the carbon sequestration cost function which is to be estimated. That is some land uses characteristics (afforestation/reforestation, sustainable agricultural practice and deforestation halted) are excluded from the cost function

Table 2
Descriptive Statistics of the Data.
Source: Computed from Data Analysis, 2016.

Variable	Mean	Std. Dev.	Minimum	Maximum
Total Cost (TC)	4,321,239	5,872,792	109,127	1.98E + 07
Clean Development mechanism (CDM)	0.31579	0.477567	0	1
Reforestation Rate (RR)	31.94737	34.90061	2	100
Sustainable Agriculture Practice (SAP)	0.694737	0.563199	0.1	2.5
Deforestation (D)	159.2632	172.5987	0	740
Deforestation Halt (DH)	14.5	16.01697	0	64.6
Forest Area (FA)	26,074.98	35,053.61	2347.4	153,200.8
Gross Domestic Product (GDP)	3197.106	3412.633	581.1246	15,548.26
Carbon Sequestration Supply (CSS)	12.56842	18.33737	1.3	83.8

Table 3
Result of the data normality test.
Source: Computed from the Data Analysis, 2016. S.D. = Standard Deviation.

Variables	Mean	Median	S. D.	Kurtosis	Skewness	S. Wilk (W)	P–Value
LnTC	14.413	14.476	1.459	− 0.379	− 0.167	0.968	0.741
LnRR	2.766	2.995	1.318	− 1.228	− 0.083	0.986	0.989
LnSAP	− 0.651	− 0.511	0.806	− 0.168	− 0.247	0.977	0.908
LnD	4.402	4.753	1.564	5.195	− 1.530	0.831	0.003
LnDhalt	2.106	2.241	1.259	1.717	− 0.942	0.932	0.187
LnFA	9.595	9.434	1.065	0.198	0.403	0.975	0.876
LnGDP	7.739	7.679	0.784	0.925	0.562	0.970	0.779
LnCSS	1.991	1.960	1.004	0.519	0.466	0.977	0.896

though these variables have impact on cost function through the endogenous variable carbon sequestration. These variables are considered as excluded exogenous variables. This means that the exclusion principle of instrumental variable exists in the carbon sequestration cost function. The endogenous variable, carbon sequestration (CSS) is functionally related to the omitted or excluded land use variables. This was done to capture the effect of excluded or omitted variables in carbon sequestration supply function (Sargan, 1958). In addition, it is assumed that there might be some measurement errors in the variables because those were collected from different sources. Thus, this study is conducted using the instrumental variable approach (IV regression). The data was analysed using STATA 11.1 software.

Total Cost (TC) of carbon sequestration represents the dependent variable. The independent variables are Carbon Sequestration Supply (CSS), presence of Clean Development Mechanism (CDM) projects, GDP (in PPP). In addition, the CSS function also depends on some land use change like Deforestation Halts (DH), Afforestation/Reforestation (AF/RF), Sustainable Agricultural Practice (SAP) and Forest Area (FA) respectively. According to Lubowski et al. (2006), land capability class is another important variable in carbon sequestration cost estimation. In this study however, data on land capability class for individual country in Africa is not available. Hence are not included in the specified carbon sequestration cost function. In order to carter for the problem of omitted variable in the estimation, Instrumental Variable (IV) regression was used. IV regression is used when some variables are assumed to be omitted or excluded from the models which are correlated with the explanatory variables but unobservable (Sargan, 1958). Thus, it is used to obtain a consistent estimator of unknown coefficients of the population parameters when regressor X is correlated with the error term (u) (Stock and Watson, 2006).

Furthermore, IV regression is also used in case of simultaneous causality bias (where explanatory variable causes dependent variable and dependent variable causes explanatory variable) and errors in variables (Aldrich, 1993 and Gujarati, 2004). Amount of carbon sequestration derivable in a country is dependent on land use change characteristics like afforestation/reforestation, deforestation, sustainable agricultural practice and deforestation halted. It implies that land use change characteristics variables have impact on cost function through the endogenous variable carbon sequestration. Hence, these variables are considered as excluded exogenous variables. This means that the exclusion principle of instrumental variable exists in the carbon sequestration cost function, as the endogenous variable carbon sequestration (CSS) is functionally related to those omitted or excluded land use variables. In addition, it is assumed that there might be some measurement errors in the variables because those were collected from different sources. Thus, the estimation was done using the IV regression. However, if we assumed that the carbon sequestration cost function has no endogenous regressors, the model specification will follow Eq. (B.3). Otherwise, it will be expressed as Model 1 (Appendix B). Based on these considerations, two IV regression models were specified as stated Model 1and 2 in Eqs. (B.1) and (B.3) respectively.

To ascertain the choice of model selection between Model 1 and 2, test for endogeneity was conducted for model 1. If no endogeneity exists, thus, we would conclude that carbon sequestration supply is not a function of land use change characteristics. Hence, model 2 will represent the basis for discussion. This is because of the omitted variable – land capability class of which the observed data is not available. The usage of OLS regression (Model 3) was to compare with the result of other models (Appendix B).

3.4. Marginal cost estimation method

The marginal cost reveals the amount of dollar ($) required to achieve additional unit of land being converted from the existing use to land use in favour of carbon sequestration. The Marginal Cost (MC) was estimated as the product of the individual Average Cost (AC) and the estimated coefficient of carbon sequestration supply variable. AC for each country was extracted from Deveny et al. (2009). In order to obtain MC, the partial derivate of Eq. (A.9) was taken with respect to carbon sequestration supply (Appendix C).

For profit maximization, the necessary condition is Marginal Cost (MC) = Marginal Revenue (MR) But in a competitive market MR is equal to the price. Thus, Marginal Cost (MC) = Price (P). Therefore, MC is the price (or cost) of carbon in each country.

Total cost (TC) was estimated as a product of carbon sequestration supply (CSS) and average cost (AC), measured in ton per USD (ton/$).

4. Results and discussions

4.1. Distribution of average cost of carbon sequestration

The description of the data was done to compare cost of carbon sequestration among African countries as against the entire developing countries (i.e. Africa and other nations) as presented by the study. The chart (Fig. 1) shows the distribution of average cost of carbon

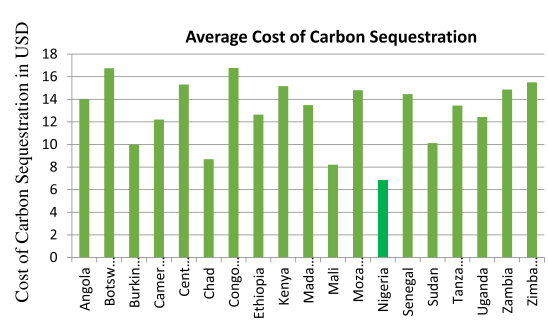

Fig. 1. Distribution of average cost of carbon sequestration.
Deveny et al. (2009).

Table 4
IV regression of total cost against the independent variable (N = 19).
Source: Computed from the Data Analysis, 2016.

Independent variables	Model 1 Ivreg (2sls)	Model 2 Ivreg (2sls)	Model 3 OLS
Constant	6.841	10.675	10.675
	3.252	3.802	5.240
	(2.10)***	(2.81)***	(2.04)***
Carbon Sequestration Supply	1.353	0.502	0.502
	0.358	0.361	0.497
	(3.78)***	(1.39)	(1.01)
Gross Domestic Product	0.625	− 0.206	− 0.206
	0.370	0.39	0.538
	(1.69)**	(− 0.53)	(− 0.38)
Clean Development Mechanism	0.111	0.437	0.437
	0.579	0.512	0.705
	(0.19)	(0.85)	(0.62)
Reforestation Rate		− 0.034	− 0.034
		0.185	0.253
		(− 0.18)	(− 0.13)
Sustainable Agriculture		0.379	0.379
		0.294	0.405
		(1.29)	(0.94)
Deforestation Halt		0.828	0.828
		0.541	0.745
		(1.53)	(1.11)
Forest Area		0.754	0.754
		0.305	0.419
		(2.48)***	(1.80)**
Deforestation		− 1.010	− 1.010
		0.414	0.572
		(− 2.44)***	(− 1.77)**
R^2	0.412	0.676	0.671
Wald Chi^2	15.36	36.73	2.55
Df	(3, 11)	(8, 10)	(8, 10)
F (P-value)	0.000	0.000	0.083

The shaded figures are the estimated standard errors. Figures in parenthesis are the t – value of the estimated coefficient. ** & *** indicate significance level at 10% and 1% respectively.

sequestration in each of the countries. The result shows that the majority have their cost of carbon sequestration per ton being estimated below $14. Botswana and Congo DRC represent African countries with high cost of carbon sequestration with $16.75 and 16.77 respectively. Nigeria however, has her average cost of carbon sequestration as low as $6.82. This implies that Nigeria stands higher chance of benefiting from carbon trade market against other countries in Africa as most developed nations (Annex I Countries) are currently in search of relatively low carbon price (Lubowski et al., 2006). In general, the distribution implies that most African countries are suitable for cost effective carbon sequestration technology (i.e. forest based carbon sequestration).

4.2. Estimation of carbon sequestration cost function

The overall result shows that the IV regression ($p < 0.01$) and OLS ($p < 0.10$) were both significant at 1% and 10% respectively. The result of the estimation was presented in Table 4. This implies that IV regression shows higher level of fitness than the OLS estimation. Also, the t-statistics in IV regression is higher than that of the OLS estimation. This shows that IV regression is more precise as it has less standard error than the OLS. The test for endogeneity was conducted for model 1. The result shows that the test statistics (Wu-Husman F-test and Durbin-Wu-Husman Chi-square test) are insignificant following the estimated p–values of 0.2046 and 0.1441 respectively. This implies that estimating the equation with non-linear regression (log-log) gives a consistent result. Thus, we cannot reject the null hypothesis of repressors' endogeneity. We therefore conclude that is there is no endogeneity problem in the model.

The result revealed that carbon sequestration supply ($p < 0.01$) and Gross Domestic product ($p < 0.01$) are the factors influencing cost of carbon sequestration among the selected SSA countries (Model 1). The non-significant variables included in the model are kept because of their theoretical relationship with cost of carbon sequestration (as explained in the cost modelling) and their significance in other study (Nobi, 2013).

In Model 1, the result showed that carbon sequestration cost function depends on carbon sequestration supply variable ($p < 0.01$). However, carbon sequestration supply is a function of land use changes like afforestation/reforestation, sustainable agricultural practice, deforestation halted, deforestation and size of forest area. Thus, increasing these land use change elements affect the carbon sequestration through changing land use characteristics. If a change in any of these determinants increases the volume of carbon sequestration, it will also increase the cost. This is because land use in favour of other activity will be affected (i.e. reduced). These variables work as instrument in the carbon sequestration which in turn affects the cost function. The Gross Domestic Product ($p < 0.10$) though was significant however, we do not consider it for explanation following the fact that we were 90% sure of its effect on the dependent variable.

In Model 2, forest area ($p < 0.01$) significantly affects the cost of carbon sequestration ($p < 0.01$). If the size of a forest increases, it will increase the volume of carbon sequestration. As forest is considered as the sink of atmospheric carbon, it is expected that the area of forest is proportionately related to the volume of carbon sequestration. That is, the more the forest sink capacity increases the more the sequestration increases. Thus, increase in forest land area would bring about reduction in cost of carbon sequestration.

Deforestation ($p < 0.01$) exerts a significant effect on cost carbon sequestration among SSA countries. The coefficient of this variable was negative which implies that increasing deforestation will results in increased cost of carbon sequestration among these countries. Studies have shown that rate of forest destruction is SSA is enormous (FAO, 2003; Okojie and Akinwunmi, 2011). Increasing rate of forest clearance in SSA would lower the chance of the region from benefiting from carbon trade participation.

4.3. Carbon cost estimation

The marginal cost estimation which is the cost per unit land area to drive land use change towards carbon sequestration was estimated at $13.30 /ton/ha (Table 5). The estimate indicates a relatively low cost of carbon sequestration among the selected SSA countries as against the abatement of carbon among the developed nations (Ellerman and Decaux, 1998; USA - $186; European Union; $273, Japan; $584). This implies all the selected countries are suitable supplier of carbon sequestration for the developed nations. However, several developed nations are in search of a very low cost of carbon sequestration as low as $1 (Lubowski et al., 2006), thus, implies that countries with the lowest marginal cost would be of best interest among all other countries. In that wise, Nigeria with a marginal cost of approximately $7.0 would stand the chance of benefiting more from carbon trade investment than all other SSA countries. Next on the line would be Mali and Chad with an approximate marginal cost of $8.0 and $9.0 respectively. It should however be noted that other factors like volume of carbon sequestered per hectare of land, available land area or forest area influences the choice of country of carbon trade investment. The cost of carbon sequestration however remains the principal component that dictates what each country stands to gain from carbon trade while other factors can be modified.

5. Conclusion

The study revealed that carbon sequestration cost function among African countries is dependent of carbon sequestration supply. This however is a function of land use change characteristics like forest area, deforestation, reforestation, deforestation halt and sustainable

Table 5
AC, TC and MC of carbon sequestration estimates per country.
Source: Computed from Data Analysis (2016) **Indicates countries with lowest marginal cost.

Countries	Average Cost (AC) (USD)	Total Cost (TC) (USD)	Marginal Cost (MC) (USD)
Angola	13.98	99.258	14.38542
Botswana	16.75	21.775	17.23575
Burkina Faso	9.99	23.976	10.27971
Cameroon	12.21	212.454	12.56409
Cent. Afri. Rep.	15.31	225.057	15.75399
Chad	8.7	34.8	8.9523**
Congo DRC	16.77	1405.326	17.25633
Ethiopia	12.65	78.43	13.01685
Kenya	15.17	28.823	15.60993
Madagascar	13.49	207.746	13.88121
Mali	8.21	27.914	8.4481**
Mozambique	14.81	79.974	15.23949
Nigeria	6.82	72.974	7.0178**
Senegal	14.46	63.624	14.87934
Sudan	10.12	216.568	10.41348
Tanzania	13.45	260.93	13.84005
Uganda	12.43	103.169	12.79047
Zambia	14.86	126.31	15.29094
Zimbabwe	15.51	48.081	15.95979
Average	12.93		13.30

agriculture practice. Of all the land use change characteristic, deforestation and land use conversion to forest area significantly affect the cost of carbon sequestration. This implies that the cost of carbon sequestration among African countries can be lowered if their land use change is tailored towards ensuring carbon sequestration supply. For instance, increasing forest estate will lead to increased carbon sequestration supply.

The estimated cost of carbon sequestration in the study appears more realistic among SSA. This is because, a number of factors that affect land-use decisions in practice among SSA has were considered but which are difficult to measure explicitly and include in engineering and optimization models.

The study however suggests that positive land use change should be encourage among countries in Africa, (particularly in Nigeria with the least marginal cost of carbon sequestration). This will help in reducing cost of carbon sequestration and thereby lowering the global effect of climate change. Similarly, African countries should concentrate effort towards increasing their forest estates as this will enhance their chances of benefiting from carbon trade market.

Appendix A. Land use optimization theory

$$\text{Max} \prod = P^{Q}Q(A^{Q}) + P^{S}S(A^{S}) - C^{Q}(A^{Q}) - C^{S}(A^{S}) \tag{A.1}$$

Subject to

$$A^{Q} + A^{S} \le A_0 \tag{A.2}$$

Here

Π = Profit of a land owner,
Q = Quantity of output from agricultural or any other land used sectors,
S = Total quantity of carbon sequestered,
P^Q = Price of agricultural output,
P^S = Price of carbon,
A^Q = Land uses in agricultural sector,
A^S = Land uses in forestry sector,
C^Q = Cost of land uses in output production,
C^S = Cost of land uses in forestry.

$$\text{Max } L = P^{Q}Q(A^{Q}) + P^{S}S(A^{S}) - C^{Q}(A^{Q}) - C^{S}(A^{S}) + [A_0 - A^{Q} - A^{S}] \tag{A.3}$$

$\{A^Q, A^S\}$
Here.
L = Lagrangian profit function,
λ = Lagrangian multiplier (i.e. shadow price/cost of land uses).
So, the FOCs for profit maximization are,

$$\partial L/\partial A^{Q} = P^{Q}\{\partial/\partial A^{Q}\}\, Q(A^{Q}) - \{\partial/\partial A^{Q}\}C^{Q}(A^{Q}) - \lambda = 0 \tag{A.4}$$

$$\partial L/\partial A^{S} = P^{S}\{\partial/\partial A^{S}\}\, Q(A^{S}) - \{\partial/\partial A^{S}\}C^{S}(A^{S}) - \lambda = 0 \tag{A.5}$$

$$\partial \lambda/\partial A^{Q} = A_0 - A^{Q} - A^{S} \tag{A.6}$$

From Eqs. (A.4) and (A.5), λ becomes

$$\begin{aligned}\lambda &= P^{Q}\{\partial/\partial A^{Q}\}\, Q(A^{Q}) - \{\partial/\partial A^{Q}\}C^{Q}(A^{Q}) \\ &= P^{S}\{\partial/\partial A^{S}\}\, Q(A^{S}) - \{\partial/\partial A^{S}\}C^{S}(A^{S})\end{aligned} \tag{A.7}$$

$$\lambda = \prod A^{Q} = \prod A^{S} \tag{A.8}$$

Here

$\Pi A^Q = \partial\Pi/\partial A^Q$ = refers marginal return of land used in agriculture sector and.
$\Pi A^S = \partial\Pi/\partial A^S$ = refers marginal return of land used in carbon sequestration sector.

Appendix B. Econometric model estimation

Model 1:

$$\ln TC = \alpha_1 + \alpha_2 \ln X_1 + \alpha_3 X_2 + \alpha_4 \ln X_3 + \varepsilon \tag{B.1}$$

While the $\ln X_1$ is a function of several instrumental variables and thus lnX_1 can be expressed as,

$$\ln CSS = \mu_1 + \mu_2 \ln DH + \mu_3 \ln RF + \mu_4 \ln SAP + \mu_5 \ln FA + \mu_6 \ln DF\, \theta \tag{B.2}$$

Model 2:

$$\ln TC = \alpha_1 + \alpha_1 \ln X_1 + \alpha_3 X_2 + \alpha_4 \ln X_3 + \alpha_5 \ln X_4 + \alpha_6 \ln X_5 + \alpha_7 \ln X_6 + \alpha_8 \ln X_7 + \alpha_9 \ln X_8 \tag{B.3}$$

Where,

TC = Total Cost ($)
X_1 = Carbon Sequestration Supply (ton)
X_2 = Clean Development Mechanism Project (1 = yes, 0 otherwise)
X_3 = Gross Domestic Product ($)
X_4 = Deforestation Halted (ha per year)
X_5 = Reforestation Rate (ha per year)
X_6 = Sustainable Agriculture Practice (ha)
X_7 = Forest Area (ha)
X_8 = Deforestation (ha)
ε and θ = error terms,
α_1 and μ_1 = intercepts
$\alpha_2 - \alpha_9$ and $\mu_2 - \mu_6$ = coefficients to be estimated.

Appendix C. Marginal cost estimation

$$\frac{1}{TC}\frac{\partial TC}{\partial CSS} = \alpha_2 \frac{1}{CSS} \tag{C.1}$$

$$\frac{\partial TC}{\partial CSS} = \alpha_2 \frac{TC}{CSS} \tag{C.2}$$

$$\frac{\partial TC}{\partial CSS} = MC, \quad \frac{TC}{CSS} = AC \tag{C.3}$$

$$MC = \alpha_2 * AC = f(CSS) \tag{C.4}$$

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